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Quantitative Evaluation of Transverse Cracks and Delamination in Cross-Ply Laminates Using Lamb Wave Velocity

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This paper proposes a quantitative evaluation method for transverse crack density and delamination length in cross-ply laminates using Lamb wave velocity. We found experimentally that both the stiffness and the velocity decreased as the transverse crack density increased. In contrast, the stiffness decreased but the velocity increased as the delamination length increased. We analytically deduced the relationship between the velocity and the crack density from a combination of a shear-lag analysis and the classical plate theory. We also confirmed that the Lamb wave propagated through the 0° layers in the delaminated regions, and formulized the relationship between the velocity and the delamination length. The predicted crack density and delamination length using the measured velocity were in good agreement with the experimental results. The present method is a simple and quick NDT technique, thus promising for structural health monitoring of composite structures.

Key word: Fiber-reinforced plastics, Transverse crack, Delamination, Lamb wave, Non-destructive evaluation

1. INTRODUCTION

Composite laminates are advantageous as structural components for aircraft and spacecraft because of their superior specific strength and stiffness. However, damage detection in composite laminates is difficult due to the anisotropy of the materials and the fact that much of the damage often occurs beneath the top surface. Furthermore, conventional NDT techniques, such as x-radiographic and ultrasonic C-scan, are very time consuming and expensive. Structural health monitoring (SHM) systems for composite structures have thus recently become a focus of attention to reduce maintenance costs and improve safety and reliability. There is a practical need for a monitoring system that can detect damage quickly and reliably; the conventional method can be used to characterize any damage found in detail.

Damage such as transverse cracking, delamination, or fiber breakage occurs when composite laminates are subjected to mechanical and thermo-mechanical loading. Transverse cracking, one of the most frequently encountered types of damage in composite laminates, can be detrimental to the stiffness and dimensional stability. One serious concern is that transverse cracks may become leak paths when composite laminates are applied as structural components for liquid fuel tanks. They induce local stress concentrations at the crack tips and cause initiation of delamination. Delamination also develops easily under impact and may cause significant loss of strength or stiffness.

Ultrasonic Lamb waves offer a convenient approach to evaluate composite laminates because they can propagate a long distance and their velocities are sensitive to the in-plane stiffness of laminates. Many studies have been conducted to detect transverse cracks [1–3] and delamination [4–6] using the Lamb wave method. The ability to detect and also quantitatively evaluate damage is necessary for SHM systems.

In this study, we measured the stiffness and Lamb wave velocity for GFRP and CFRP cross-ply laminates with various transverse crack densities and delamination lengths. The relationships between the damage and the stiffness were deduced from a shear-lag analysis. Furthermore, we formulized changes in the velocity as functions of the crack density and delamination length using a shear-lag analysis and the classical plate theory, then compared the predicted values with the experimental results. This research led us to propose measuring the Lamb wave velocity as a simple and superior SHM system for transverse cracks and delamination in composite laminates.

2. THEORETICAL BACKGROUND

We will briefly introduce the analytical procedures for predicting the S_0 mode velocity and the quantitative relationships between the stiffness and the transverse crack density and delamination length in this section.

Only the S_0 mode and the A_0 mode propagate for thin plates at low frequencies below 1 MHz. The S_0 mode is almost nondispersive and the A_0 mode is highly dispersive in this region. The velocities of both modes are directly related to the properties of the materials; the S_0 mode velocity has a higher dependence on the in-plane stiffness than the A_0 mode. Furthermore, the S_0 mode velocity is much higher than that of the A_0 mode, thus the leading part of the detected waveform is easily identified as the S_0 mode. Therefore, the S_0 mode velocity is useful for evaluating stiffness changes caused by damage. The velocity of the S_0 mode for the principal axis of the orthotropic laminate is simply expressed by the classical plate theory as [3]

$$V \approx \sqrt{\frac{E}{\rho}} \tag{1}$$

where E is the Young's modulus, ρ is the density of the laminate.

Stiffness reduction of cross-ply laminates with transverse cracks and delaminations can be derived from a complete parabolic shear-lag analysis [7], which yields a fairly good approximation of the strain and stress distributions obtained by the finite element method.

Normalized stiffness reduction in cross-ply laminates with equally distributed transverse cracks and with a pair of delaminations that developed from the crack tips can be expressed as [7, 8]

$$\frac{E_x}{E_x^0} = \left(1 + \frac{t_{90}}{t_0}\frac{E_{90}}{E_0}\frac{2t_{90}D}{\eta}\tanh\frac{\eta}{2t_{90}D}\right)^{-1} \qquad (2)$$

$$\frac{E_x}{E_x^0} = \left[1 + \frac{t_{90}}{t_0}\frac{E_{90}}{E_0}\left(x + \frac{2t_{90}}{\eta L}\tanh\frac{\eta L}{2t_{90}}\right)\right]^{-1} \qquad (3)$$

where E_x and E_x^0 are the Young's moduli of the damaged and undamaged laminates. t_0 and t_{90} are the half thicknesses, and E_0 and E_{90} are the Young's moduli of the 0° and the 90° layers. D is the crack density, L is the gauge length of the extensometer, x is the delamination ratio, which is defined as the delamination length divided by L, and η is the shear-lag parameter.

3. EXPERIMENTAL PROCEDURES

3.1 Specimen preparation

The materials studied were E-glass/TX23235 (GFRP) and T800H/3631 (CFRP) cross-ply laminates. These composite plates (300 mm × 300 mm) were fabricated with unidirectional prepregs by a hot-press machine in accordance with the manufactures' recommended processes. Tensile coupons (200 mm × 15 mm) for each laminate were cut from the plates and the GFRP end tabs were glued. Table I shows the measured material properties of the unidirectional GFRP and CFRP laminates. We used these values to predict the stiffness reduction due to the damage and the S_0 mode velocity.

Table I Properties of unidirectional GFRP and CFRP laminates

Property	GFRP	CFRP
Longitudinal Young's modulus, E_{11} (GPa)	39.5	157.6
Transverse Young's modulus, E_{22} (GPa)	10.95	8.67
Longitudinal shear modulus, G_{12} (GPa)	4.03	3.83
Transverse shear modulus, G_{23} (GPa)	3.10	3.40
Poisson's ratio, ν_{12}	0.32	0.38
Ply thickness (mm)	0.097	0.134
Density, ρ (kg/m^3)	1910	1571

3.2 Measurement of the Lamb wave velocity

Figure 1 shows the experimental setup for measuring the S_0 mode velocity. Low-frequency (below 500 kHz) Lamb waves were generated using spike waves to excite a sending transducer (Fuji Ceramics, Model M5W). A sending transducer with a diameter of 5 mm and a pair of AE sensors (Fuji Ceramics, Model M304A) with diameters of 4 mm were mounted on the specimens via a coupling gel. The detected signals were amplified and transferred to a digital oscilloscope, which averaged 100 samples to improve the signal-to-noise ratio. Arrival times of the S_0 mode at a pair of AE sensors were determined using the zero-cross method. We calculated the S_0 mode velocity by dividing the distance between the AE sensors (100 mm) by the difference in the arrival times.

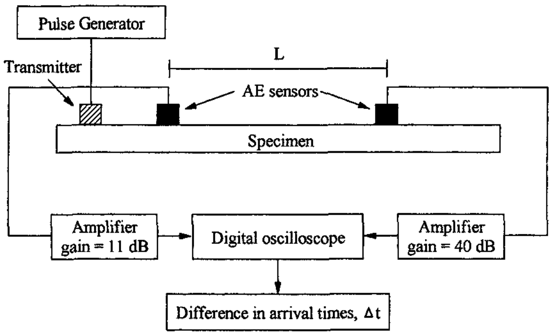

Fig. 1 Experimental setup for measuring S_0 mode velocity.

4. RESULTS AND DISCUSSION

4.1 Quantitative evaluation for transverse crack density

4.1.1 Experimental procedures

The specimens used for this study were CFRP cross-ply laminates with stacking sequences of $[0/90_6/0]$, $[0/90_8/0]$, and $[0/90_{10}/0]$. We performed tensile tests to introduce transverse cracks and measure the stiffness. The strain was measured during the tests by an extensometer with a gauge length of 50 mm. Tensile loading was halted when some acoustic emissions were heard; the number of transverse cracks was observed using an optical microscope. The specimens were then removed from the machine, and the S_0 mode velocity was measured, as illustrated in Fig .1. We repeated these procedures until final failure and confirmed that only transverse cracks (no delamination) were initiated and that all the cracks penetrated through the specimen width. We first performed tensile tests without artificial flaws. However, we observed fewer than five cracks along the gauge length before the final failure. We therefore introduced artificial flaws with intervals of about 1 mm on the 90° layers at an edge of the specimen with a knife within the gauge length. Thus, we experimentally obtained the relationships between crack density, stiffness, and S_0 mode velocity.

4.1.2 Stiffness reduction due to transverse cracks

Figure 2 shows the experimental results of the normalized stiffness as a function of crack density for CFRP specimens. The stiffness decreased as the crack density increased. Figure 2 also depicts the results deduced from the analytical model as solid lines for a comparison with the experimental ones. The stiffness reduction depended on the thickness of the 90° layers; the reduction increased as the thickness of the 90° layers increased. The predicted values were in good agreement with the experimental ones for all laminates.

4.1.3 S_0 mode velocity change due to transverse cracks

Figure 3 depicts the experimental results of the normalized S_0 mode velocity as a function of crack density. The velocity decreased as the crack density increased similar to that observed for the stiffness. If we

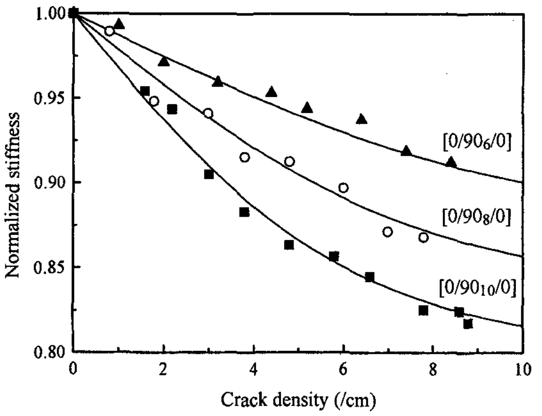

Fig. 2 Experimental and predicted normalized stiffness as a function of crack density for CFRP cross-ply laminates.

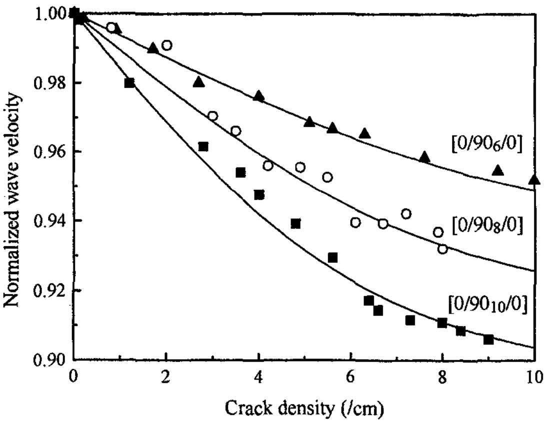

Fig. 3 Experimental and predicted normalized S_0 mode velocity as a function of crack density for CFRP cross-ply laminates.

assume that the velocity in a cracked laminate obeys the classical plate theory as expressed in Eq. (1), then the normalized S_0 mode velocity as a function of crack density D can be derived using Eqs. (1) and (2) as

$$\frac{V_x}{V_x^0}=\left(1+\frac{t_{90}}{t_0}\frac{E_{90}}{E_0}\frac{2t_{90}D}{\eta}\tanh\frac{\eta}{2t_{90}D}\right)^{-\frac{1}{2}} \tag{4}$$

where V_x and V_x^0 are the S_0 mode velocities for damaged and undamaged laminates.

We compared the predicted results deduced from Eq. (4) as solid lines in Fig. 3. The predicted values were in good agreement with the experimental ones for all laminates. These results indicate that Lamb waves propagate through a cracked laminate with a velocity in accordance with the classical plate theory. These results led us to conclude that we can quantitatively evaluate the number of transverse cracks by simply measuring the S_0 mode velocity.

4.2 Quantitative evaluation for delamination length

4.2.1 Experimental procedures

We observed no delamination in the tensile tests, as described in the previous section. Therefore, we created delaminations by inserting two 20 μm-thick PTFE sheets at the upper and lower interfaces between the 0° and the 90° layers. We fabricated six specimen coupons (200 mm × 15 mm) for GFRP and CFRP cross-ply laminates with stacking sequences of $[0/90_8/0]$. One of them was intact, and each of the others had a pair of delaminations of different lengths. The delaminations were 10, 20, 30, 40, and 50 mm long by 15 mm wide. The 0° layers in the delaminated region curved outward after curing due to a difference in the thermal expansion coefficients of the 0° and 90° layers. The PTFE sheets were peeled, and a tensile load was then applied to the coupon, which created a transverse crack in the 90° layers between the delaminated regions. Thus, we released the thermal residual strain and fabricated simulated delaminations that developed from the crack tips. We measured the stiffness and the S_0 mode velocity as functions of the delamination length using these specimens.

4.2.2 Stiffness reduction due to delamination

Figure 4 shows the experimental results of the normalized stiffness as a function of the delamination ratio for GFRP and CFRP specimens. Figure 4 also depicts the results deduced from the analytical model as solid lines for comparison with the experimental results. The stiffness decreased as the delamination ratio increased. The predicted values were in appropriate agreement with the experimental ones.

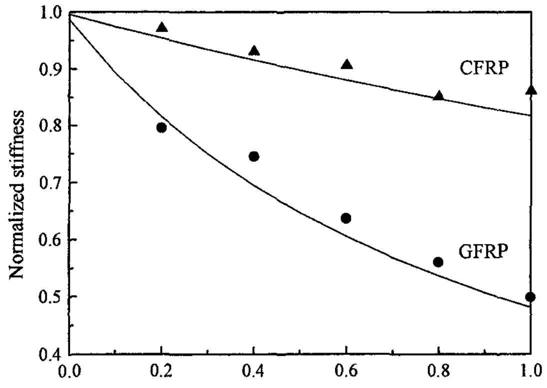

Fig. 4 Experimental and predicted normalized stiffness as a function of the delamination ratio for GFRP and CFRP cross-ply laminates.

4.2.3 S_0 mode velocity change due to delamination

Figure 5 depicts the experimental results of the normalized S_0 mode velocity as a function of the delamination ratio, which is defined as the delamination length divided by the interval of a pair of AE sensors. Unexpectedly, the velocity increased as the delamination ratio increased. Furthermore, the sensitivity of the velocity to delamination in CFRP was greater than that in GFRP, in contrast to the situation for transverse cracks [9]. The obtained S_0 mode velocities for GFRP and CFRP specimens with delaminations 50 mm long (delamination ratio = 1) were 4897 m/s and 10785 m/s. These values were almost the same as the velocities of the 0° layers for each material. We modeled the Lamb

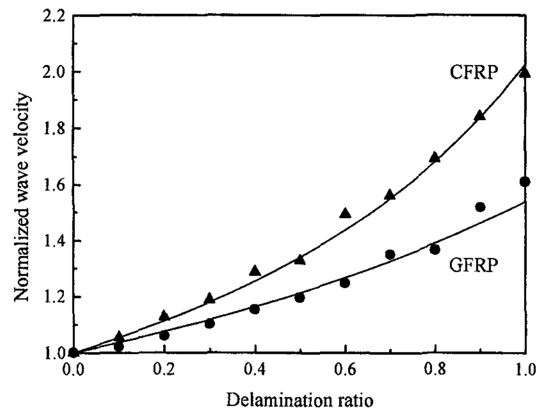

Fig. 5 Experimental and predicted normalized S_0 mode velocity as a function of the delamination ratio for GFRP and CFRP cross-ply laminates.

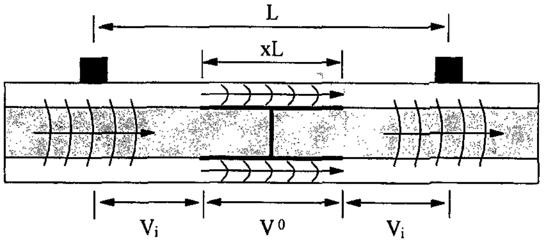

Fig. 6 Lamb wave propagation model in a delaminated cross-ply laminate.

wave propagation based on these results, as illustrated in Fig. 6. A Lamb wave propagates with the initial velocity before delamination, and separates and propagates through the 0° layers between the delamination regions. The Lamb wave velocity then returns to the initial value. We formulized the relationship between the S_0 mode velocity and the delamination ratio based on this model, as expressed in Eq. (5).

$$\frac{V_d}{V_i} = \frac{V^0}{xV_i + (1-x)V^0} \qquad (5)$$

where V_d and V_i are the S_0 mode velocities of the delaminated and intact laminates, and V^0 is the S_0 mode velocity of the 0° layers. We ignored the reduction of the S_0 mode velocity near the delamination tips in the analysis because the effects were very small.

Figure 5 also depicts the predicted normalized S_0 mode velocity as a function of the delamination ratio as solid lines for the GFRP and CFRP laminates. The predicted values deduced from Eq. (5) were in very good agreement with the experimental results. In contrast to the transverse cracks, interfacial continuity between the 0° and 90° layers is no longer retained in delamination. Therefore, the combination of the shear-lag analysis and the classical plate theory is useless for predicting the delamination length.

We confirmed that a Lamb wave propagates through the 0° layers in the delaminated regions. Considering this fact, the delamination length evaluated by the present method corresponds to the delamination length projected orthographically that was evaluated by an x-radiographic. Thus, we can evaluate not only the length of a single delamination but also the sum of the lengths of multiple delaminations using this method.

It is very important to note that the present method is a simple and quick NDT method, qualities that are required for a SHM system. Our research has enabled us to propose measurement of the S_0 mode velocity as an excellent SHM system for evaluating transverse cracks and delamination in cross-ply laminates.

5. CONCLUSIONS

This study was undertaken to establish a simple and quick SHM system for quantitative damage evaluation in cross-ply laminates using the Lamb wave velocity.

We first investigated the effects of transverse cracks on the S_0 mode velocity in CFRP cross-ply laminates. The velocity decreased as the transverse crack density increased. We analytically deduced the relationship between the velocity and the crack density. The predicted crack densities were in good agreement with the experimental ones. We confirmed that the S_0 mode velocity obeys the classical plate theory even in cracked laminates.

We then investigated the effects of delamination on the S_0 mode velocity in GFRP and CFRP cross-ply laminates. We fabricated simulated delaminations that developed from crack tips for this investigation. The velocity increased as the delamination length increased. We experimentally confirmed that the Lamb wave propagated through the 0° layers in the delaminated region. We used the Lamb wave propagation model to formulize the relationship between the velocity and the delamination length. The predicted delamination lengths were in good agreement with the experimental ones.

Our research has enabled us to demonstrate that measuring the S_0 mode velocity is an excellent SHM system for evaluating transverse cracks and delamination in cross-ply laminates.

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